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A simple method for evaluating the trapping performance of acoustic tweezers

Ying Li,[a)] Changyang Lee, Kwok Ho Lam, and K. Kirk Shung
NIH Transducer Resource Center and Department of Biomedical Engineering, University of Southern California, Los Angeles, California 90089-1111, USA

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The purpose of this paper is to present a rapid and simple method to evaluate the trapping performance of high frequency focused ultrasonic transducers for acoustic tweezer applications. The method takes into consideration the friction between the particle to be trapped and the surface that it resides on. As a result it should be more reliable and accurate than the methods proposed previously. The trapping force produced by a 70-MHz press-focused transducer was measured to evaluate the performance of this approach. This method demonstrates its potential in optimizing the excitation conditions for acoustic tweezer applications and the design of acoustic tweezers. © *2013 American Institute of Physics*. [http://dx.doi.org/10.1063/1.4793654]

Since the invention of optical trapping in 1970s,[1,2] it has been developed as a powerful tool with broad applications in biology and physics.[3] The mechanisms of optical trapping in two limiting cases were explained by two different models. When the trapped spherical particle size and the wavelength of the trapping laser satisfy the conditions of Mie scattering, the optical forces can be predicted by the Ashkin's ray-optics model.[4] When the trapped spherical particle size and the wavelength of the trapping laser satisfy the conditions of Raleigh scattering, the optical forces can be predicted by the Harada and Asakura's electromagnetics model.[5] It has been interesting to find that an acoustic beam has similar trapping effects to a laser beam. Single beam acoustic trapping of microparticles under the conditions of Mie scattering was theoretically and experimentally demonstrated by Lee.[6,7] Similar to the mechanisms of optical trapping, the intensity gradient of the acoustic microbeam and the difference of acoustic impendence between microparticles and the medium induce a net acoustic radiation force (gradient force) towards the beam axis. This force could be used to trap a microparticle. This kind of devices was termed single beam acoustic tweezers.[7] With the advent of high frequency transducers technology, ultrasound microbeam generated by tightly focused transducers was demonstrated to be capable of immobilizing a single leukemia cell[8] and trapping a single microparticle as small as 5 μm.[9] It has been suggested that acoustic tweezers may have a wide variety of biomedical and physical applications, as optical tweezers. Moreover, acoustic tweezers have several advantages over optical tweezers, for instance, lower cost, deeper penetration depth in light opaque media and less biological damages.[10]

However, it has been quite a challenge in developing acoustic tweezers with acceptable trapping performance. High quality acoustic tweezers must satisfy a few criteria that include high sensitivity, low f-number, and the acoustic beam being radically symmetrical about the beam axis. Previously, several methods, namely, a press-focused method,[9,11] a self-focused method,[9] a lens-focused method,[12] and a phased array-focused method,[13] were undertaken in the authors' laboratory to develop the high frequency focused transducers for acoustic tweezer application. Each method has its advantages and disadvantages. For instance, the press-focused method has an advantage of simple fabrication process, but the mechanical pressing process could easily break the piezoelectric material, therefore affecting the performance of the transducers. The self-focused method is relatively easy to fabricate the transducer with low f-number ($\sim$1) and consistent quality, but the sensitivity of the self-focused transducers is usually poor. Lens-focused transducers would incur extra attenuation caused by the lens especially in ultrahigh frequency range. Phased array transducers could focus and steer the acoustic beam; therefore, no mechanical movement of transducer is required. However, the cost of array transducers is much higher than that of single element transducers. In addition the excitation condition of the transducer would also affect the performance of the transducers. In order to determine the suitable fabrication method and optimize the excitation condition for acoustic tweezer application, a simple and accurate method is required to evaluate the trapping performance of the transducer.

Previously, three different methods have been reported to calibrate the trapping force from optical tweezes, i.e., equipartition theorem method,[14] power spectrum analysis method,[15] and viscous drag force method.[16] In order to apply the first two methods to calibrate the trapping force generated from acoustic tweezers, very high speed position detection systems with fast computational capability are needed. Currently, only the viscous drag force method has been applied to calibrate the trapping force form acoustic tweezers. In such an approach, the trapping force was calibrated against the known viscous drag forces. Here additional experiment was required to generate a calibrated flowing fluid, and the calibration of drag forces from the flowing fluid may induce additive measurement errors. Moreover, the friction force on microparticles was neglected for the sake of simplicity.[16,17] Since the direction of friction force coincides with that of the trapping force but against that of the viscous drags force, the actual value of the trapping force is overestimated without considering the frictional effect.

[a)]Author to whom correspondence should be addressed. Electronic mail: yli582@usc.edu.

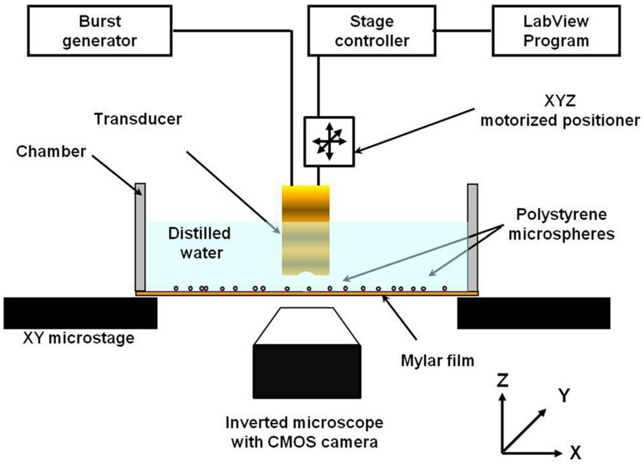

FIG. 1. Experimental configuration for a single beam acoustic tweezer experiment.

In this study, a rapid and reliable method in which the friction force on the microparticle was included and assumed to be a constant was proposed to calibrate the trapping force generated by acoustic tweezers. Fig. 1 illustrates the general configuration for the single beam acoustic tweezer experiment which was usually performed in a chamber with an acoustically transparent mylar film as the bottom structure. The chamber was filled with distilled water and microparticles or cells were placed on the surface of mylar film as trapping targets. The acoustic tweezer was mounted on a motorized 3-axis positioner above the chamber. The trapping targets were placed at the focal point of the acoustic tweezer by mechanically adjusting the position of the acoustic tweezer using the positioner. The motion of the trapped microparticle was detected by an inverted microscope (IX-71, Olympus, Japan) and images captured by a CMOS camera (ORCA-Flash 2.8, Hamamatsu, Japan).

In most cases, the concave shape of the transducer surface focuses the reflected light into a point that is projected on the mylar film as a light spot. As shown in Fig. 2, the light spot could be used to indicate the lateral position of the focus of transducer. After the acoustic tweezers trapped a microparticle, the microparticle could follow the motion of the focus of acoustic tweezers if the acoustic tweezers was moved at a relative low velocity by the positioner. However, if the moving velocity of acoustic tweezers was increased, the microparticle would eventually fail to follow the motion of acoustic tweezers. As shown in Fig. 3, an initial acceleration phase exists in the general motion pattern of positioner to increase the velocity from zero to a desired value. As the time of the acceleration phase is fixed, the value of acceleration increases with the desired velocity. Actually, most of trapping failures happen at this default acceleration phase. It is because the trapping force only needs to overcome the friction force (F_f) in the constant velocity phase while an extra force ($F_f + ma$) is required to produce an acceleration of the microparticle as that of the acoustic tweezers. If the trapping force was not strong enough, the microparticle would fail to follow the motion of acoustic tweezers. It can be described by the following mathematical expression:

$$\frac{F_{t\max} - F_f}{m} = a_{\max} < a_{AT}, \tag{1}$$

where $F_{t\max}$ is the maximum trapping force exerted by acoustic tweezers on the microparticle, F_f is the friction force on the microparticle, m is the mass of the microparticle, $a_{\max}$ is the maximum acceleration that the microparticle could reach, and a_{AT} is the acceleration of acoustic tweezers.

A simple method was thus deduced from the above mechanism for evaluating the trapping performance of the acoustic tweezers. The maximum acceleration of microparticle can be estimated by gradually increasing the acceleration of acoustic tweezers until the microparticle cannot follow, and the effective trapping force ($F'_{t\max}$) is the difference between the maximum trapping force of acoustic tweezers ($F_{t\max}$) and friction force (F_f). It can be easily calculated with Newton's second law

$$F'_{t\max} = F_{t\max} - F_f = ma_{\max}. \tag{2}$$

By assuming a constant friction force, the effective trapping force is directly related to the trapping performance of

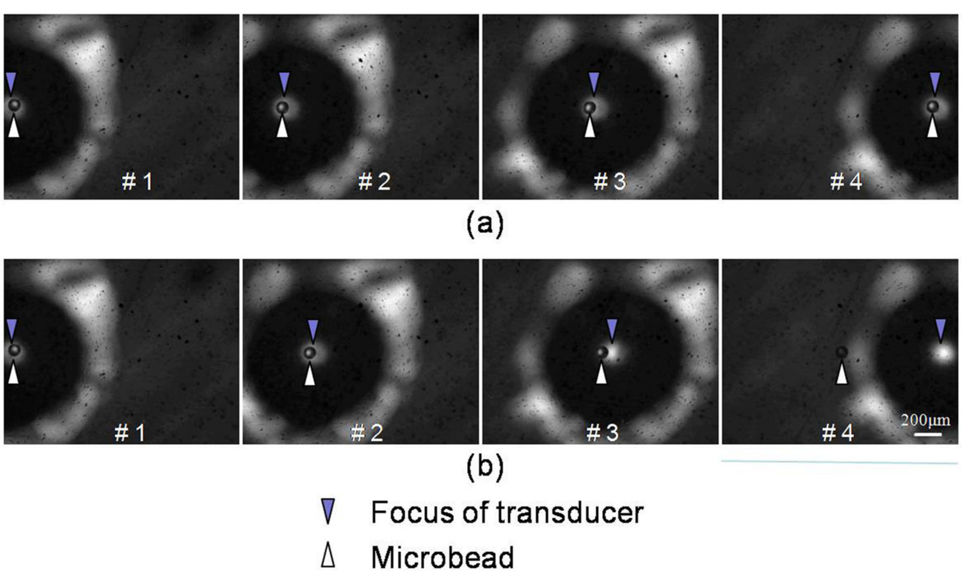

FIG. 2. Demonstration of a polystyrene microsphere (90 μm mean diameter) manipulated by an acoustic tweezer. (a) The acoustic tweezer was moving at a relative low acceleration ($a_{AT} = 5000\ \mu$m/s^2), the polystyrene microsphere could follow the motion of the acoustic tweezer. (b) The acoustic tweezer was moving at a relative high acceleration ($a_{AT} = 5500\ \mu$m/s^2), the polystyrene microsphere failed to follow the motion of the acoustic tweezer. Images were captured by a CMOS camera (ORCA-Flash2.8, Hamamatsu, Japan) (enhanced online) [URL: http://dx.doi.org/10.1063/1.4793654.1].

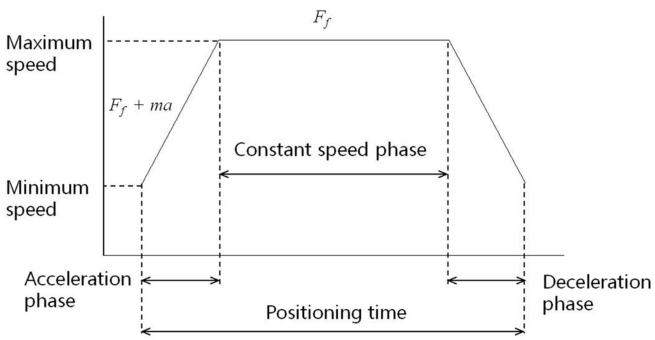

FIG. 3. General motion pattern of the XYZ positioner.

acoustic tweezers. Therefore, $F'_{t\max}$ should be considered as an important parameter to reflect the actual trapping performance of acoustic tweezers.

To put this idea into the practice, the trapping performance of a 70-MHz press-focused transducer under different excitation conditions were evaluated by the proposed method. Pertinent data on this transducer are summarized in Table I. A polystyrene microsphere of 90 μm diameter (Microbead NIST traceable particle size standard, 90 μm, Polyscience, Inc.) was used as a trapping target. The mass of polystyrene microsphere was calculated from its volume and density. A XYZ positioner (SGSP 20, Sigma KOKI Co., Japan) controlled by a stage controller (SHOT 202, Sigma KOKI Co., Japan) was employed to manipulate the position of the acoustic tweezer. A Labview program was customized to generate various acceleration motion patterns of the positioner in X and Y directions, and the constant speed phase was minimized or eliminated to reduce the total distance of the whole motion. After a polystyrene microsphere was trapped by the acoustic tweezer, the positioner was moved at a constant acceleration in X or Y direction. The acceleration of positioner was increased by 500 μm/s^2 each time until the polystyrene microsphere could not follow the motion of acoustic tweezer. The maximum acceleration of the acoustic tweezer is assigned as $a_{\max}$, which was further confirmed by fine adjusting the acceleration of acoustic tweezer, as shown in Fig. 2. The $a_{\max}$ of acoustic tweezer was measured under different driving conditions. Two groups of measurement were performed: In one the pulse repetition period was 1 ms and the duty factors varied from 1% to 4% while the input voltage was applied at 15.8 V_{pp}. In another the input voltage was increased from 12.6 V_{pp} to 31.6 V_{pp}, while the duty factor was fixed at 1.5%. The final results were averaged from 5 measurements at different locations of mylar film. $F'_{t\max}$ was calculated and displayed as functions of duty factor and input voltage in Figs. 4 and 5, respectively. The results show that the effective trapping force increases with duty factor and

TABLE I. Specifications of a 70-MHz ultrasonic transducer.

Material	Lithium niobate
Aperture size	2.6 mm
Frequency	70 MHz
Focal length	4.0 mm
f-number	1.5
−6 dB bandwidth	33%

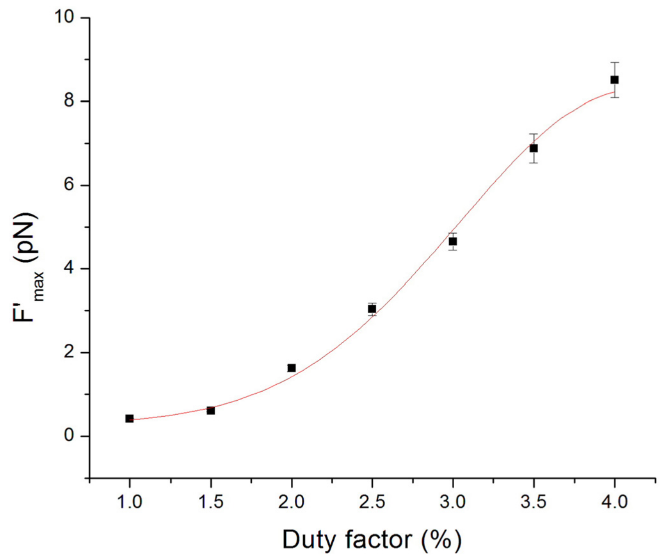

FIG. 4. $F'_{t\max}$ of a 70-MHz acoustic tweezer as a function of duty factor (with a constant driving voltage of 15.8 V_{pp}).

input voltage. Both trends exhibit a nonlinear behavior, which could be divided into four stages for explanation. At the very beginning of a low driving power stage, the single microsphere cannot be trapped because the trapping force is smaller than the friction force. Afterwards, with increasing the driving power, the microsphere can be trapped until the trapping force is slightly larger than the friction force. At this low driving power stage, $F'_{t\max}$ can only increase slightly with the driving power. When the driving power was gradually increased, the trapping force would increase and become much larger than the friction force, resulting in a large slope as shown in Figs. 4 and 5. Viscous drag force caused by the water might play a factor as the driving power was further increased, corrupting the effective trapping force measurement.

These results indicate that the effective trapping force of the 70-MHz transducer was in the range of a few piconewtons. The value is smaller than the reported data.[17] It may be

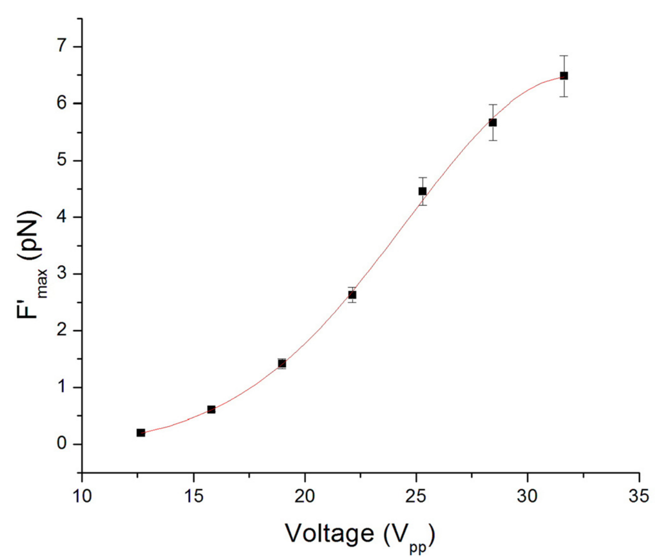

FIG. 5. $F'_{t\max}$ of a 70-MHz acoustic tweezer as a function of input voltage (with a duty factor of 1.5%).

because the transducer used in this study has a higher frequency and larger f-number. Furthermore, as mentioned above, the friction force worked on the trapped microparticle was not considered in the previous force calibration methods. Moreover, in many applications, the microsphere usually was attached to an object of interest as a "handle" to apply the calibrated force.[3] While the microsphere transmits the trapping force to the object of interest, the friction force also works on the microsphere. Therefore, the effective trapping force determined in the present work may better estimate the force received by the object of interest. It is also worthwhile to point out that current force calibration methods are only practical with a spherical object whereas the proposed calibration method mainly depends on the acceleration allowing it to be applied to objects of different shapes.

The trapping force of acoustic tweezers was supposed to be evaluated as a function of acoustic intensity because it may provide more quantitative information of the trapping performance. However, as there are difficulties in accurately measuring the output from the transducers at 70 MHz with current available technology, excitation voltages are reported in lieu of acoustic intensity. Besides, since the friction force varies with the speed of particle movement, the calibration and compensation of the friction force need to be carefully addressed and will also be pursued in the future.

In summary, a simple method was introduced to more accurately estimate the trapping force produced by acoustic tweezers by taking the frictional effect into consideration. Experiments carried out show that the effective trapping force of acoustic tweezers increases nonlinearly with two excitation parameters. The results suggest that this method may provide a more accurate way to evaluate the trapping performance of acoustic tweezers, useful for the determination of the optimal driving conditions and the better design of high performance acoustic tweezers.

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